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Granroth-Wilding H.M.V.[1 + #], Daunt F.[2], Cunningham E.J.A.[1]* & Burthe S.J.[2]*

1. Wellcome Centre for Infection, Immunity and Evolution/Institute of Evolutionary Biology, University of Edinburgh, Ashworth Laboratories, Charlotte Auerbach Road, Edinburgh EH9 3FL, UK
2. NERC Centre for Ecology & Hydrology, Bush Estate, Penicuik EH26 0QB, UK
[+] Corresponding author: Hanna Granroth-Wilding; hanna@granroth-wilding.co.uk; +44 (0)7971 119505
[#] Current address: Department of Biosciences, University of Helsinki, Viikinkaari 1, P.O. Box 65 00014 Helsinki, Finland
*Equal author contributions

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ABSTRACT

Parasite infection in young animals can affect host traits related to demographic processes such as survival and reproduction, and is therefore crucial to population viability. However, variation in infection among juvenile hosts is poorly understood. Experimental studies have indicated that effects of parasitism can vary with host sex, hatching order and hatch date, yet it remains unclear whether this is linked to differences in parasite burdens. We quantified gastrointestinal nematode burdens of wild juvenile European shags (*Phalacrocorax aristotelis*) using two *in situ* measures (endoscopy of live birds and necropsy of birds that died naturally) and one non-invasive proxy measure (faecal egg counts). *In situ* methods revealed that almost all chicks were infected (98%), that infections established at an early age, and that older chicks hosted more worms, but faecal egg counts underestimated prevalence. We found no strong evidence that burdens differed with host sex, rank or hatch date. Heavier chicks had higher burdens, demonstrating that the relationship between burdens and their costs is not straightforward. *In situ* measures of infection are therefore a valuable tool in building our understanding of the role that parasites play in the dynamics of structured natural populations.

Keywords: Parasite burden, endoscope, dissection, *Contracaecum*, anisakid, seabird, macroparasite, prevalence, FEC, demographic trait, growth, host-parasite interaction

KEY FINDINGS

- We quantified nematode burdens of seabird chicks using necropsy, endoscopy and FECs
- *In situ* techniques showed 98% prevalence, early establishment and higher burdens with age
- Faecal egg counts, a proxy measure, underestimated prevalence
- Chicks with higher burdens weighed more, contrary to expectations if infection is costly
- Endoscopy of juveniles enables monitoring of wild hosts' infections across their lifetime

INTRODUCTION

The costs that parasite infection can impose on their hosts can influence key demographic traits, such as reproductive success and survival, which are crucial to the growth rate and hence viability of populations (Albon et al., 2002; Newey et al., 2005; Redpath et al., 2006, Tompkins 2011). However, parasitism is unlikely to affect all individuals in a population in the same way. Firstly, individuals may host different burdens as a result of differences in exposure to parasites, susceptibility to infection and resistance to its impacts. This contributes to parasite abundance typically showing a skewed distribution among hosts, which is particularly well documented in macroparasites (Randolph et al., 1999; Shaw and Dobson, 1995). Secondly, once parasitized, the relationship between parasite load and host fitness may vary between individuals due to differences in tolerance for a given parasite load. Siblings, for example, may vary in the level of maternal antibodies they receive (Pihlaja et al., 2006), males may be affected more than females due to immunosuppressive effects of testosterone (Mougeot et al., 2009), and the relative benefits of allocating resources between fighting infection and reproduction may vary with age (Adamo et al., 2001). These factors may lead to different types of host responding differently to infection, with consequences for key host traits related to fitness such as weight gain during critical periods of growth. Understanding how parasite burdens and their impacts on hosts vary between different classes of individual may therefore be crucially important for understanding the impacts of parasites on heterogeneous host populations.

A key process for population viability is the level of offspring recruitment to the breeding population. Understanding how parasitism impacts on the juvenile subset of the population is therefore important for modelling population growth. Infection in early life can alter juveniles' developmental trajectories (Fitze et al., 2004; Romano et al., 2011), with potentially life-long fitness consequences that may further influence demographic processes such as reproduction and survival long after recruitment (Lindström, 1999; Metcalfe and Monaghan, 2001; Monaghan, 2008). However, despite the importance of early-life infection, between-individual patterns of parasitism and the development of infections in juvenile hosts have not been widely investigated in the wild. Although young hosts have been shown to exhibit systematic between-individual differences in their response to experimental infection or anti-parasite treatments according to characteristics such as hatching order (Granroth-Wilding et al., 2014), sex (Romano et al., 2011) or timing of breeding (Reed et al., 2008), it remains unclear whether variation in response is associated with differences in

burden or differences in tolerance. Thus, quantifying individual parasite burdens across the juvenile component of the population, where individuals' responses to infection are also known by measuring key fitness-related traits, is central to accurately predicting parasite impacts at the population level.

Quantifying parasite burdens is logistically challenging in the wild, particularly for endoparasites that often make up the majority of a host's parasite biomass (Hoberg, 2005). Necropsy allows direct counts of parasites in the host and is widely considered to give the most reliable measure. However, this destructive method prevents longitudinal studies, which are crucial for detecting associated fitness consequences such as recruitment probability and future reproductive success (Fitze et al., 2004). In juvenile hosts, such sublethal impacts typical of macroparasites have the potential to affect key demographic parameters over a range of timescales; avoiding destructive sampling is therefore particularly important to understand the full fitness consequences of infection in young hosts. Moreover, necropsy may not be viable for hosts of conservation importance. Faecal egg counts (FECs) are a common non-destructive and non-invasive proxy measure of endoparasite burden (e.g. Bowman and Georgi, 2009; Craig *et al.* 2006; Seivwright *et al.* 2004), but may not always reflect true parasite burden due to variable rates of helminth egg production (Shaw and Moss, 1989; Tompkins and Hudson, 1999), poor sensitivity at low burdens (Levecke *et al.* 2009), and not representing larval helminths that do not produce eggs but can nonetheless be costly to the hosts (Fagerholm and Overstreet, 2008). Recent work in wild adult seabirds has pioneered endoscopy as an additional, direct and reliable method to obtain an index of gastrointestinal nematode burdens in live individuals (Burthe et al., 2013). This approach has great potential for quantifying the development of an individual's infection from an early age, but has not previously been applied to juveniles in the wild.

Here, we use two *in situ* measures of parasite burden – necropsy and endoscopy – and the proxy measure of FECs to quantify patterns of between-individual variation in the trophically-transmitted gastrointestinal nematode burden of juvenile European shags (*Phalacrocorax aristotelis*, henceforth “shag”), a piscivorous seabird. Experimental manipulations of parasite load in adults and chicks has shown that responses to treatment vary with host phenotype: treatment of parents increases male chicks' survival, particularly late in the season, but not female chicks' (Reed et al., 2008); treatment of chicks generally affects the growth rate of last-hatched siblings but not the older brood members (Granroth-Wilding et al., 2014); and the impact of simultaneous treatment of parents and their offspring differs between early- and late-nesting families (Granroth-Wilding et

al. 2015). Endoscopy of adults has found males to host more worms than females and late breeders more than early breeders (Burthe et al., 2013), but among juveniles, patterns of variation in parasite abundance and their link with variation in host fitness are not well quantified. It is hence unclear whether these differences in treatment responses between types of juveniles arise from differences in nematode burden or differences in the impact of a similar burden. Moreover, the link between parasite burden and demographically important host traits is unexplored. Our objectives were therefore to: 1. quantify individual parasite burdens of juveniles using two *in situ* methods, endoscopy and necropsy, and compare these to a proxy measure of prevalence based on FECs; 2. identify whether burdens vary with host age, sex, hatching order and hatch date; 3. examine whether natural variation in parasite abundance is associated with a fitness-related trait, host mass.

METHODS

Host-parasite system

This study was carried out in 2012 in the breeding population of shags on the Isle of May National Nature Reserve in south-east Scotland (56º11 N, 2º33 W) that has been the subject of an individual-based long-term demographic study for several decades. Shags are sexually dimorphic, with males growing faster to reach an adult size c. 20% bigger than females (Daunt *et al.* 2001). The modal clutch size in this population is three eggs and these hatch asynchronously, with the second and third siblings (B and C chicks) hatching on average 1 and 2-3 days after the first (A chick). This asynchrony results in a hierarchy of size within the brood, in which youngest siblings generally grow more slowly and have higher mortality but are more plastic in response to changing environmental conditions than their older counterparts (Granroth-Wilding *et al.* 2014; Stokland and Amundsen, 1988). Breeding success declines through the season, with later breeders fledging fewer chicks and producing fewer recruits (Daunt *et al.* 1999; Harris *et al.* 1994).

Shags on the Isle of May are infected with the gastrointestinal nematode *Contracaecum rudolphii* (Anisakidae: Ascaridoidea; Hartwich 1964), which occur in the GI tract of nestling and adult shags in this population (Reed 2007; Burthe *et al.* 2013; E. Harris, pers. comm.; S. Burthe, J. Chantrey & D. Kowalek, unpublished data). All but one of 146 naturally infected adults endoscoped to date have hosted worms, with wide variation in burdens from 2 to >80 worms (Burthe *et al.* 2013; S. Burthe & E. Butterfield, unpublished data). *C. rudolphii* is a widely distributed seabird specialist, now recognised to comprise a complex of morphologically similar species (Anderson,

2000; Fagerholm and Overstreet, 2008; Hoberg, 2005; Moravec, 2009). Nestling shags obtain regurgitate fish directly from their parents' throats and are infected with larval worms in the fish tissue. Direct infection of chicks with adult worms dislodged from the parent's proventriculus could also occur during feeding, but the importance of this transmission route is not well understood (Dubinin, 1949; Fagerholm and Overstreet, 2008; Hoberg, 2005; Huizinga, 1971). Anisakid infection can cause costly pathology at attachment sites such as inflammation, necrosis, haemorrhaging and perforation of the stomach wall (Hoberg, 2005; Kuiken, 1999; McClelland, 2005), which may be compounded by secondary bacterial infections (Fagerholm and Overstreet, 2008), and is expected to activate a costly immune response (Colditz, 2008; Hasselquist and Nilsson, 2012). Moreover, *Contracaecum* is thought to feed on fish ingested by the bird and thus directly competes with the host for resources (Abollo *et al.* 2001; Anderson, 2000; Dubinin, 1949; Huizinga, 1971).

Quantifying nematode burdens

We quantified the nematode burden of individual shag chicks using two *in situ* techniques, endoscopy of targeted individuals or necropsy (dissections) of a subset of the study population that died naturally during a severe storm. We also conducted faecal egg counts (FECs) on faecal material collected opportunistically from both endoscoped and dissected chicks (all detailed methods below). Not all individuals produced faecal samples, precluding FECs, and no birds were both endoscoped and dissected, as endoscoped chicks were not sacrificed and endoscopy of dead animals is not reliable (S. Burthe, unpublished data).

Endoscopy

We used a refurbished 9mm diameter medical endoscope (Olympus©, UK) to view the oesophagus and proventriculus of conscious chicks under licence (full details of endoscopy procedure in (Burthe *et al.* 2013). Endoscopy was undertaken by a trained and experienced operator (S. Burthe) while an assistant held the bird still and its bill open. A cloth was placed over the bird’s eyes to reduce stress while the endoscope operator inserted the endoscope into the proventriculus. All worms that were visible were counted as the endoscope was slowly withdrawn from the bird. We noted whether the worms were large or small. Visibility was scored on a scale of 1 to 5 (worst to best, as in Burthe *et al*. (2013)) and included in all analyses as poorer visibility could hinder accurate quantification. Endoscopy was carried out when chicks were large enough for the

endoscope to be comfortably inserted, around 25 days of age. Throughout the process, there was no evidence of discomfort (e.g. rapid breathing). All endoscoped chicks resumed normal behaviour immediately on being returned to the nest and all fledged successfully. All endoscopy was carried out early in the morning, before parents had returned with the first food load of the day, to avoid views being obstructed by recently ingested food.

At endoscopy, chicks were assigned a rank in the brood hierarchy according to size: in broods of three, the heaviest two chicks were designated AB and the lightest C, and in broods of one or two, all chicks were designated AB. Wing length was used as an additional indicator if mass difference was not greater than 20g. Mass at day 25-30 accurately identifies the last-hatched chick in 83% of cases but only distinguishes the first- and second-hatched (A and B) in 47% of cases, whereas A and B are accurately assigned as AB in 89% of cases (data from 27 nests, with three chicks surviving to day 10, in 2010 and 2011 with accurate hatch dates; Granroth-Wilding *et al.* 2014). We used chick mass at endoscopy as an indicator of chick performance. At endoscopy age, the majority of growth is completed (Daunt *et al.* 2001), and fledging mass has been shown to correlate with recruitment in a range of species (Magrath, 1991; Schwagmeyer and Mock, 2008). All endoscoped chicks were blood sampled for molecular sexing (Griffiths *et al.* 1996).

In total, we endoscoped 45 chicks in 20 nests, of which 18 were undisturbed before endoscopy and 27 were sham-treated controls from a parallel parasite-removal experiment (full details in Supplementary Information; no individuals treated with anti-parasite drugs are included in the results presented here), injected with 0.05ml saline solution at age 10-12 days and subsequently weighed at ages 10, 15 and 25 days. A subset of chicks that remained safely accessible as they got older and more mobile were endoscoped twice (2 untreated chicks and 4 sham-treated).

Necropsy

Sacrificing individuals for systematic necropsies was not possible as this would prevent longitudinal investigations of the link between parasite burden and host survival, and moreover removing individuals from this long-term study population is not desirable. However, in 2012, there was an unusually prolonged period of rain and cold weather in the middle of the peak chick-rearing period, lasting over two days. This caused considerable natural juvenile mortality due to waterlogging and chilling of chicks that were still downy (not yet waterproof) but too large to be efficiently sheltered by their parents. Mortality was thus not a direct consequence of overall poor condition nor of parasitism, though both factors may have contributed. Similar weather-related mass mortality

events of chicks during the breeding season have only occurred once in the last 15 years, so this was a rare opportunity to obtain a sample of birds for dissection. When the weather improved and it was safe to approach nests, c. 12-36 hours after death, we collected 28 carcasses (median 20 days old, interquartile range 18-26 days; median hatch date 27th May, IQR 21st-29th May; cf. endoscoped chicks, median age 31 days, IQR 28-34 days, median hatch date 17th May, IQR 15th-22nd May). Nine of these were sham-treated controls from the parallel experiment. We also collected 6 further carcasses resulting from other natural mortality, found within a day of death, for necropsy (median age 25 days, IQR 25-29 days; median hatch date 2nd June, IQR 20th May-3rd June). For the 10 dissected chicks that were not of known age, we estimated age from wing length based on the growth rate of chicks from the same year with known hatch dates (Wing = 5.81 x Age – 27.75; in mixed model accounting for repeated measures within chick, $F_{1,147} = 9795$, $p < 0.001$; without random effects, $r^2 = 0.954$). We assigned ranks to dissected chicks in cases where the whole brood could be assessed either dead or alive, based on the structural measure of wing length: in broods of three, the two chicks with longest wings were assigned AB and the shortest C, and in broods of one or two, all chicks were assigned AB. A sample of blood or tissue was taken from every carcass for molecular sexing (Griffiths *et al.* 1996).

Where possible, carcasses were dissected fresh within 6 hours of recovery, or kept at +4°C for up to 24 hours (16 carcasses). If dissections could not be carried out within this time (17 carcasses), they were stored at -20°C for up to one week and defrosted before dissection. The proventriculus was removed together with 3cm of oesophagus and small intestine. The removed gastrointestinal portion was then opened out using one medial ventral cut and the stomach contents thoroughly examined, then rinsed with water through a fine mesh. The body cavity was examined for evidence of nematodes migrating away from the proventriculus following host death, and we additionally examined the whole intestine of four individuals; no other visible macroparasites were found (further descriptions in Supplementary Information). All worms were counted, removed and stored in ethanol. To obtain an index of the maturity of the infection in the bird, during which stage *Contracaecum* undergoes substantial growth (Fagerholm and Overstreet, 2008), worms were categorized into size classes based on width (>0.75mm wide, large; <0.5mm wide, small; 159 out of 1436 worms (11%) in between the categories).

Faecal egg counts (FECs)

During endoscopy, we opportunistically collected faecal samples from 19 chicks that defecated

during handling, and from 24 dissected chicks, we obtained a faecal sample from the cloaca after carcasses had been frozen at -20°C for long-term storage. All faecal samples were therefore stored at -20°C after collection; previous work in this system has given no evidence that freezing affects egg counts or prevalence (Supplementary Information). FECs were carried out using a flotation technique (Bowman and Georgi, 2009; detailed methods in Supplementary Information). Each sample was suspended in 20 ml saturated salt solution per 1 g of faeces and nematode eggs were counted in 0.45 ml (0.02 g faeces) of the suspension examined under a McMaster slide.

Statistical analysis

We first quantified patterns in parasite abundance obtained by each *in situ* parasite measure, endoscopy and dissection. We considered two aspects of nematode infection: total worm burden, indicating overall parasite abundance, and the proportion of worms that were large, which is likely to reflect the duration of the infection. We then tested whether these indices were associated with host age, as expected if chicks are exposed to infective larvae throughout their development, and with phenotypic traits known to affect responses to infection: host sex, rank (AB vs. C) and hatch date (Granroth-Wilding *et al.* 2014; Reed *et al.* 2008, 2012). Lastly, in endoscoped chicks, we examined the association between parasite abundance and chick performance by testing whether chick mass at endoscopy varied with worm count and the proportion of worms that were large.

In all analyses of dissected chicks, we excluded two outliers with high statistical leverage: one old chicks with a very high load (a male, 45 days old, hosting 243 worms; range of other chicks 8-148 worms) and one very young chick (ca. 2 days old) which was the only dissection that yielded a zero burden. Neither exclusion qualitatively affected any results. Although mortality is generally higher for C chicks in this population (Granroth-Wilding *et al.* 2014), all ranks were equally represented among endoscoped and dissected birds, as were males and females (for ranks across techniques, $\chi^2 = 4.50$, df = 2, $p = 0.105$; for sexes, $\chi^2 = 1.32$, df = 1, $p = 0.251$). Among endoscoped chicks, we confirmed that visibility score was not related to age, sex, rank or hatch date (all $p > 0.4$ in a linear model). Among endoscoped chicks, hatch date (from which age was calculated) was only available for the first-hatched chicks in each nest, so C chicks were assigned an age 2.5 days younger than their AB siblings (median age difference across 42 nests in 2010 and 2011 with accurate hatch date data) to avoid within-brood age differences confounding rank effects. Among dissected chicks, the effects of age and hatch date could only be examined in separate models as the age-specific main mortality event meant that they were closely correlated (in linear model, $r^2 = 0.72$,

$p < 0.001$). In these analyses, models containing hatch date instead of age gave almost identical fits (ΔAICc ≤ 0.1) and for brevity we present only the age models.

All analysis was carried out in R 3.0.2 (R Core Team, 2013) using the packages lme4 (Bates *et al.* 2011) and nlme (Pinheiro *et al.* 2012), using (generalised) linear mixed models (LM Ms or GLMMs). To account for repeated sampling of some individuals and non-independence of siblings within a brood, we fitted chick within nest as nested random factors to the endoscopy data, and nest as a random factor to the dissection data. Total burden was fitted as count data with poisson errors and logistic link function, and proportion of large worms with binomial errors, weighted by the total count, and a logit link function. Effect sizes for the proportion of large worms are presented as the log odds of a worm being large. Mass was modelled in a linear mixed model including log(age) and sex as fixed effects, to account for the non-linear growth curve and sexually dimorphic growth. Due to the low egg prevalence in faeces preventing robust analysis of relationships between FECs and host phenotypic traits or *in situ* worm burdens, we present only descriptive statistics of prevalence (but see Supplementary Information for a preliminary analysis).

We used an information theoretic approach to model selection (Burnham and Anderson, 2002), identifying important explanatory variables based on the best-fitting model(s) from a candidate set, which is well suited to an exploratory analysis. For each measure of parasite burden, our set of candidate models contained all combinations of the explanatory variables as main effects (age, hatch date, sex and rank, and additionally for endoscopy analyses, visibility) as well as an intercept-only (null) model. The best-fit model was the one that had the lowest AICc (corrected Akaike's Information Criterion, suitable for small sample sizes) in the set, and models with a ΔAICc ≤ 2 from the best fit model were considered an equivalent fit. Model selection based on significance testing gave the same conclusions. All parameters are presented ± 1 standard error, not back-transformed from the log (worm counts) or logit (proportion of large worms) link functions.

RESULTS

Quantifying worm burden in situ

The ages of birds available for necropsy ranged from 2 to 45 days and for endoscopy from 25 to 49 days. Worm burden measured using necropsy varied from 0 to 243 worms per chick; the youngest and oldest chicks were excluded from further analysis due to their strong leverage, giving an age range of 12–31 days and worm counts of 8 to 148 worms per chick (n = 31; mean 36.0 ± 4.9; prevalence 100%) (fig. 1). Worm burden measured using endoscopy ranged from 0 to 30 worms per chick (mean worm burden 11.7 ± 1.0 worms; prevalence 98%) (fig. 1). The proportion of large worms ranged from 0 to 35.7% (mean 12.9 ± 1.9%) by necropsy and 0 to 100% (mean 29 ± 5%) by endoscopy.

Using necropsy, the youngest chick to host large worms was aged 15 days and the oldest chick without large worms was 18 days. Using endoscopy, large worms were found in chicks from the age of 26 days, (earliest available age 25 days), although chicks with no large worms occurred up to the age of 36 days.

Visibility during endoscopy was generally poorer for chicks than for adults endoscoped in parallel studies, mainly due to the presence of semi-digested food. Visibility scores among the chicks in this study ranged from 1 to 4 (mean 2.7 ± 0.1) compared to a range of 3-5 (mean 4.24; n=17) for adult shags endoscoped in the same year (S. Burthe, unpublished data).

FECs as an indicator of worm burden

We obtained faecal egg counts from 19 endoscoped and 24 dissected chicks from birds aged 25–36 days and 12-45 days respectively. Nematode eggs were only found in one third of the 43 samples available (prevalence 37%), despite a prevalence of 99% in individuals sampled using *in situ* measures. Out of the 16 faecal samples that contained worm eggs, only 7 contained more than 1 egg (4 samples with 2 eggs, 2 with 3 eggs and one with 42) and 5 were from chicks in which no large worms were seen (1 necropsy, 4 endoscopies).

Nematode burden in relation to host traits

In necropsied chicks, aged 12–31 days, worm count was best explained by a model containing only age, with older chicks hosting more worms. A model with age and sex had similar support (table 1, fig. 2). The proportion of worms that were large was best explained by an intercept-only

model, with no host traits providing similar explanatory power (table 1, fig. 3).

Among endoscoped chicks, aged 25–49 days, total worm burden was best described by a model containing age and visibility (table 1, fig. 2), with older chicks hosting more worms and better visibility resulting in slightly higher worm counts (age effect size 0.10 ± 0.02 log(worms)/day, visibility effect size 0.10 ± 0.06 log(worms) per score increment). Age was supported in all five top models. Out of three equivalent-fit models, two contained a rank term (in addition to age, C chicks hosted -0.21 ± 0.16 fewer worms than AB chicks). The proportion of large worms was best described by a model containing only age (effect size 0.11 ± 0.04 increase in proportion of large worms/day) (fig. 3), with hatch date and rank each occurring twice in the three equivalent-fit models (in addition to age, effect of hatch date: 0.05 ± 0.00 greater proportion of large worms per day; effect of rank: C chicks 0.83 ± 0.50 greater proportion of large worms) (table 1).

A summary of the host traits identified as important to parasite abundance and size distribution by the two measurement techniques is given in table 2. For both necropsy and endoscopy, it is notable that individuals varied considerably in their parasite load, which contributed to many analyses yielding several equivalent-fit models that made it difficult to robustly identify phenotypic traits that influenced parasite load.

Effect of infection on host performance

Chick mass at endoscopy was best explained by a model containing main effects of age and worm count (table 3, fig. 4): heavier chicks were older and had higher worm counts (in best-fit model, effect of age 241.4 ± 43.2 g/log(day); effect of worm count, 11.8 ± 4.8 g/worm). There was one model of equivalent fit, which contained an additional sex term (males 62.4 ± 46.6 g heavier than females).

DISCUSSION

The juvenile period is an energetically expensive phase for an individual when the costs associated with parasite infection are likely to have substantial impacts on hosts. Despite this, in comparison to adults, there is very little information for wild juvenile hosts on patterns of parasite prevalence or abundance, particularly internal parasites. Here we have used necropsy and endoscopy, implemented for the first time in juveniles in the wild, to show that infection with gastrointestinal nematodes is near-universal among nestling shags (98% prevalence) and establishes at an early age,

and that nematode burden increases with chick age. In contrast, the common proxy measure of FECs suggested a prevalence of only 37%, demonstrating the value of endoscopy as a non-destructive index of *in situ* parasite burden. Previous studies have found chick sex, hatch date and rank to be important in determining responses to anti-parasite treatment (Reed *et al*. 2008, 2012; Granroth-Wilding *et al*. 2014, 2015), yet we found no strong evidence that worm burden varied with any of these host traits. This suggests that differences in response may arise due to variation in tolerance between the subclasses of juvenile as opposed to differences in burden. Further, contrary to predictions, we found that individuals with high worm burdens were heavier than similar-aged individuals with lower burdens.

Comparison of techniques for quantifying worm burden

Both necropsy and endoscopy captured the same main pattern of infection in chicks but unfortunately we did not have the opportunity to directly compare counts from the two techniques in the same individuals. None of the birds that suffered natural mortality had been endoscoped, endoscoped chicks could not be sacrificed for necropsy as this would prevent long-term monitoring of infection and its consequences, and endoscopy of carcasses is not feasible as reliable counts are difficult to obtain from the collapsed stomach of a dead bird. Comparisons of necropsied and endoscoped individuals was further constrained by the limited overlap in the ages of chicks used in each technique: endoscopy was carried out on generally older birds and tended to yield lower overall burdens but a higher proportion of large worms than necropsies of generally younger birds. Endoscopy may have yielded lower counts because chicks' stomachs frequently contained residual food that partially obscured the view through the endoscope, a constraint that is more easily avoided when endoscoping adults in this system (Burthe et al. 2013). Nonetheless, endoscopy counts from shags have been shown to be repeatable (Burthe et al. 2013), and our successful application of this technique to developing hosts thus opens opportunities for monitoring individuals' worm burdens from an early stage in their long lives. Moreover, both *in situ* techniques identified similar prevalences and an increase in burden with chick age, indicating that endoscopy provides a useful index of between-individual variation in worm burdens. This index has already been shown to be valuable for quantifying the effect of anti-parasite treatment in both adults and juveniles, even at low doses (Burthe et al. 2013; Supplementary Information, this study).

Necropsy, on the other hand, allows complete examination of the gut of the animal at any age and is likely to yield more accurate counts. However, as a destructive sampling technique, necropsy

388 is of limited application because removing individuals from the population is not desirable when
389 investigating longitudinal effects of parasite infection or working with protected natural
390 populations. In such cases, obtaining samples relies on natural mortality that may more strongly
391 affect certain parts of the population, such as those already paying the costs of a high parasite
392 burden. Moreover, necropsy of recovered carcasses may underestimate infection intensity due to
393 post-mortem migration of nematodes away from attachment sites. Given that the endoscope counts,
394 also likely underestimates, captured the same broad patterns of infection as necropsy, we suggest
395 that endoscopy provides an informative non-destructive index, albeit not true counts, of between-
396 host variation in total parasite burden. The repeated measurement of an index of infection intensity
397 across individuals' lives that this enables, while also allowing quantification of its long-term
398 consequences for host fitness, is likely also to be of practical use in other systems.
399 Measuring long-term patterns in individuals' parasite burdens could potentially be made more
400 logistically tractable if a non-invasive proxy for worm burden was available, such as FECs.
401 However, in our system, FECs failed to detect the same levels of infection revealed by *in situ*
402 measures. Although worms were found in 98% of all chicks examined, the majority of faecal
403 samples (63%) did not contain eggs, and faecal egg presence was not related to *in situ* worm burden
404 (Supplementary Information). This may be due in part to chicks hosting a high proportion of worms
405 that were small, likely immature and thus not egg-producing individuals. Variation in this
406 component of the parasite community may nonetheless be important for its impacts on host fitness,
407 as larval worms can still cause severe pathology and thus have non-negligible costs (Fagerholm and
408 Overstreet, 2008; H.-P. Fagerholm, pers. comm.). The limited presence and low counts of nematode
409 eggs in host faeces in this system appears to be a feature of this system, but we cannot rule out that
410 FECs more closely reflecting natural variation in true burdens could be obtained by examining
411 larger amount of faecal material (but see Supplementary Information), which is logistically difficult
412 in the field.
413
414 *Nematode burden in relation to host traits*
415 The positive relationship between worm burden and chick age is consistent with expectations that
416 chicks' infections should intensify throughout the nestling period. This increase suggests that chicks
417 are continuously exposed to either infective larvae in fish and/or adult worms dislodged from the
418 parent's proventriculus during feeding. Continuous exposure among chicks accords with the near-
419 universal prevalence of worms among endoscoped adult shags over 6 study years (S. Burthe,

unpublished data), which in turn indicates regular exposure to infected fish (Anderson, 2000; Fagerholm and Overstreet, 2008; Huizinga, 1971). Two further observations can also be interpreted as indicative both of larval worms establishing and growing inside the chick and of ongoing direct transmission of larger worms from the parent's proventriculus: the increase in the proportion of large worms with age in endoscoped chicks, and the presence of nematode eggs in the faeces of a 12-day-old chick (lowest estimates for maturation time of larval *C. rudolphii* in the definitive host, c. 1 week; Dubinin, 1949; Huizinga, 1971). Regardless of transmission mechanism, we found established nematode infections in all chicks from early on in their period of rapid growth (from 6-9 days; Daunt *et al.* 2001). This supports the potential of parasitism in juvenile shags to influence developmental trajectories and hence long-term performance and fitness in this long-lived species (Lindström 1999; Monaghan 2008).

Previous studies have found host sex, timing of breeding and hatching order to be important in shaping individual chicks' responses to anti-parasite treatment (Granroth-Wilding *et al*. 2014, 2015; Reed *et al*. 2008), yet here we found little evidence that these traits were strongly associated with worm burden. This contrasts with adult shags, which display variation in burdens related to sex and timing of breeding, traits that also affect responses to treatment (Burthe *et al.* 2013, Reed *et al*. 2008). Moreover, in our opportunistic necropsies, selective mortality may have confounded the effects of certain host traits: similarly-aged individuals that died in the storm event had similar hatch dates, for example, yet these two traits may influence infection intensity in different ways (for example, burdens increasing due to continuous exposure with age versus a seasonal increase in exposure to infective larvae) whose effects we were not able to separate.

Effect of infection on host performance

Parasitism, by definition, is considered to be costly, yet we found a positive correlation between parasite burden and chick mass, a fitness-related trait that is positively associated with recruitment in many bird species (Schwagmeyer and Mock, 2008). This correlation may arise as chicks fed at a higher rate are likely to have higher levels of exposure to parasites, yet parasite infection in both parents and chicks can also affect how resources are distributed among family members (Granroth-Wilding et al. 2014, 2015). Experimental approaches that tease apart the relative effects of exposure, burden and host condition are therefore needed to quantify the effect of parasitism on individual performance. Examining the longer-term association between juvenile worm burden and success in later life should also be a priority for future endoscopy studies in this

system, taking advantage of the non-destructive technique to quantify the accumulation of sub-lethal impacts typical of macroparasites. Such a chain of fitness effects is of particular importance where parasite infection can shape hosts' developmental trajectories and life histories (Fitze *et al.* 2004; Granroth-Wilding *et al.* 2014; Romano *et al.* 2011).

Conclusions

Measuring natural variation between hosts in parasite burdens is an essential link in understanding the role of parasites in regulating natural populations. Here, we have developed endoscopy as a non-destructive method to quantify relative parasite burdens in juveniles and revealed prevalence to be significantly higher than expected from more traditional proxy measures. Our demonstration of widespread infection that is established and increases from as early as 12 days of age highlights the potential importance of nematode infection in shaping the contribution of individual shags to population processes throughout their long life (over 20 years). However, we found no evidence to suggest that parasite burdens differ between subgroups of hosts that have previously been found to respond differently to parasite removal. Variation in tolerance among different parts of the population may therefore play a role in governing variation between hosts in how they are impacted by parasitism. Our findings suggest that endoscopy of live juveniles is an informative index of natural variation in parasite burdens, finding the same patterns of infection across the host population as the more direct but destructive index of necropsy. In addition, our results showed that relationships between parasite burden and fitness-related traits in early life are not straightforward. Hence, in combination with experimental approaches, endoscopy provides a powerful tool to link variation in nematode burden with its impact on host success across a wild animal’s life and across subgroups of the population, enabling predictions of how parasitism influences on demographic processes in structured natural populations.

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Table 1. The top five best-fitting models of worm burden (left columns) and the proportion of worms that were large (right columns) as measured by necropsy (top model set) or endoscopy (bottom model set) in relation to host phenotypic traits. Models in each set are shown in order of decreasing fit with their AICc and ΔAICc relative to the best-fit model. The candidate model set for each variable included all combinations of the following predictor variables: age, hatch date, rank, sex, and for endoscopy also visibility. In the necropsy models, age and hatch date and could not be included in the same models as they were closely correlated. Accordingly, models containing hatch date gave almost identical fits to those instead containing age; to illustrate a broader range of model fits, we show only the age models here.

Model (total worm count)	d.f.	AICc	ΔAICc	Model (proportion of worms large)	d.f.	AICc	ΔAICc
Necropsy							
Age	3	207.7	0.0	(intercept only)	2	117.5	0.0
Age + Sex	4	208.3	0.6	Rank	3	119.9	2.4
Age + Rank	4	210.2	2.5	Sex	3	120.0	2.5
Age + Sex + Rank	5	211.5	3.8	Age	3	120.0	2.6
Sex	3	215.6	7.9	Rank + Sex	4	122.7	5.3
Endoscopy							
Age + Visibility	5	320.2	0.0	Age	4	190.4	0.0
Age	4	320.4	0.2	Age + Rank	5	190.5	0.1
Age + Rank	5	321.1	0.9	Age + Rank + Hatch date	6	190.5	0.1
Age + Visibility + Rank	6	321.4	1.2	Age + Hatch date	5	190.9	0.4
Age + Visibility + Hatch date	6	322.6	2.5	Age + Visibility	5	192.5	2.1

Table 2. A summary of patterns of variation in nematode burdens between shag chicks, as quantified using necropsy or endoscopy, in relation to phenotypic host traits. Patterns were investigated in both the total worm burden (top set of variables) and the proportion of worms that were large, indicative of how long the chick had been infected (bottom set of variables). Traits that robustly affected worm measures (occurred in all equivalent-fit models) are indicated with a tick, traits that had some support (occurred in more than one equivalent-fit model) are shown with a tick in brackets, and traits with no robust effects are shown with a cross. Hatch date for dissected chicks is indicated with a dash to show that it could not be tested simultaneously with age, as they were tightly correlated.

Explanatory variable	Affects necropsy counts	Affects endoscopy counts
Total burden		
Age	√	√
Hatch date	-	x
Rank	x	(√)
Sex	x	x
Proportion large worms		
Age	x	√
Hatch date	-	(√)
Rank	x	(√)
Sex	x	x

512 Table 3. The top 5 best fit models of mass of endoscoped chicks. The set of candidate models
513 included all combinations of the following variables: worm count (measured by endoscopy),
514 log(age), sex and rank.
515

Model	d.f.	AICc	ΔAICc
log(Age) + Worm count	5	553.8	0.0
log(Age) + Worm count + Sex	6	554.6	0.8
log(Age) + Worm count + Rank	6	556.1	2.2
log(Age) + Sex	5	557.1	3.3
log(Age) + Worm count + Sex + Rank	7	557.3	3.5

Figure 1. Histograms showing the spread of worm counts from necropsy (left panel) and endoscopy (right panel). The dissection data does not show two high-leverage individuals excluded from the analysis, a hatchling with no worms and a near-fledgling with 243 worms.

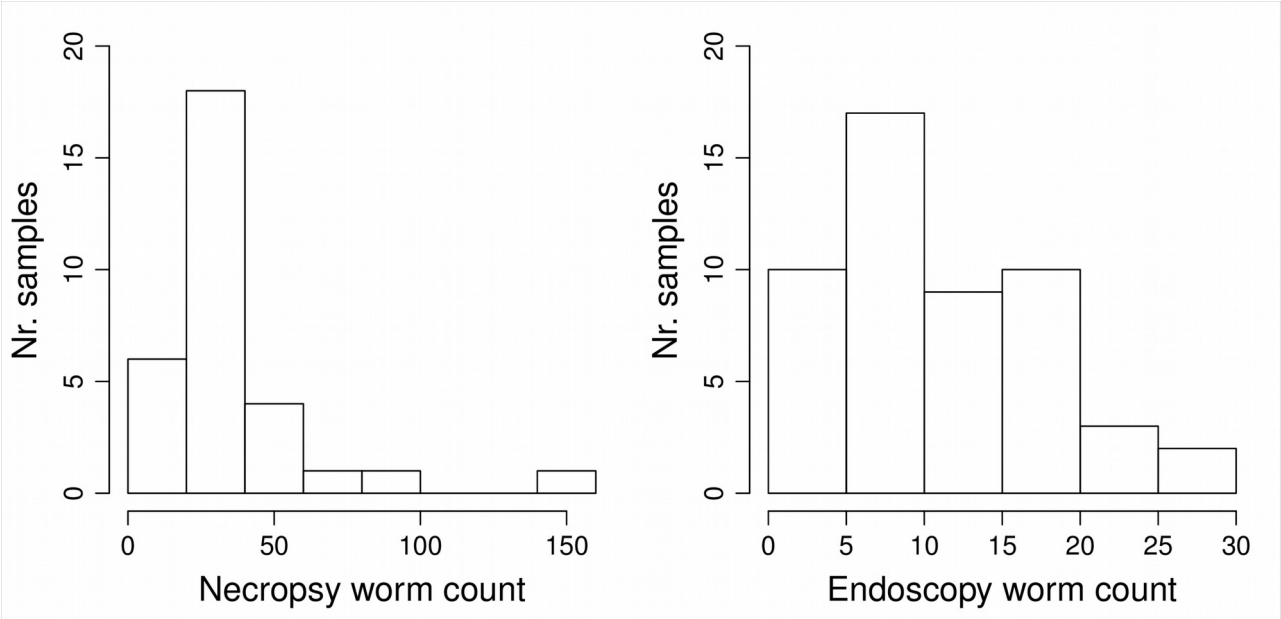


Figure 2. Total worm burden in relation to chick age for necropsied chicks (left panel) and endosocped chicks (right panel). Among endoscoped chicks (which covered an older age range than necropsied chicks) there was some evidence that rank affected worm count, and to illustrate this, in the endoscopy panel AB chicks are shown with solid symbols and C chicks with open symbols. The regression line shown is for the best-fit model, which did not include a rank term. Excluding the oldest chicks, which did not include any C chicks were found, did not alter the ordering of best-fit models. Note the difference in scale for worm counts and age ranges between the two measures. The mean lines show a fitted model without random effects using poisson errors and a log link, with 95% confidence intervals shown by the fine-dotted lines.

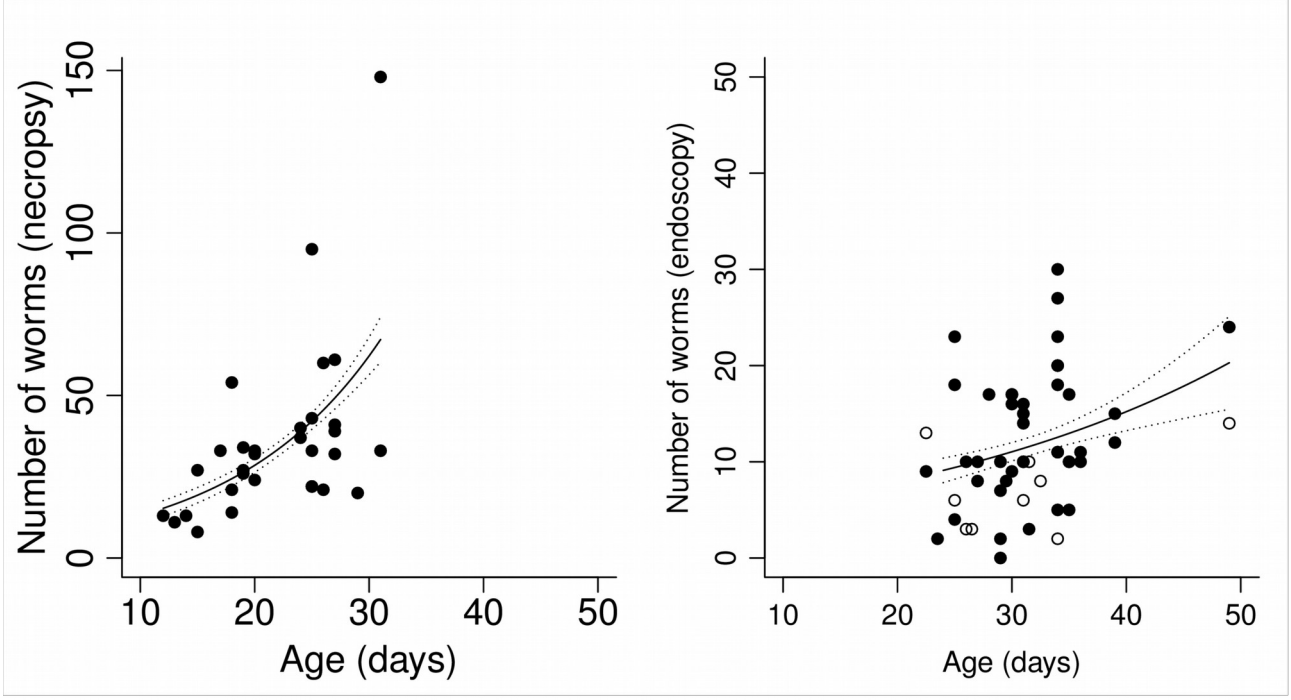


Figure 3. The proportion of worms that were large in relation to chick age for necropsied (left panel) and endoscoped (right panel) chicks. In contrast to the worm count, excluding the oldest chicks here slightly changed the order of the best-fit models to: Age + Hatch date; Age; Age + Hatch date + Rank, Age + Rank. The mean lines show a fitted model without random effects and the fine-dotted lines show its 95% confidence intervals.

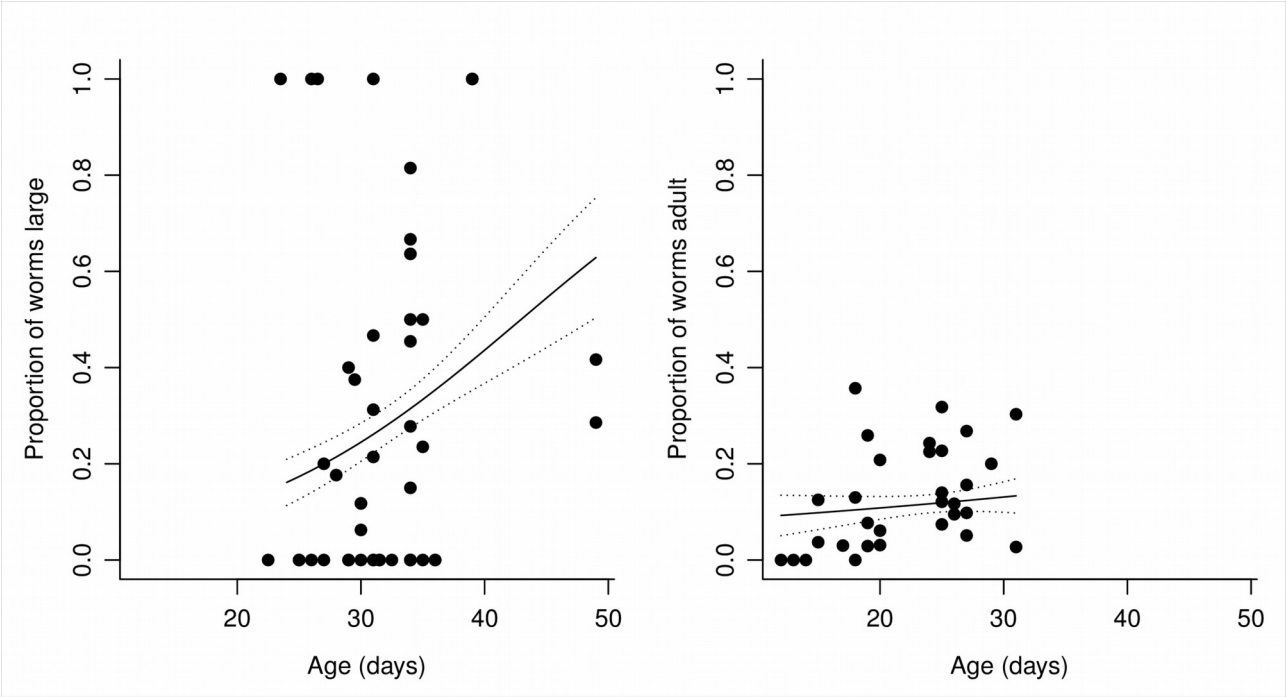
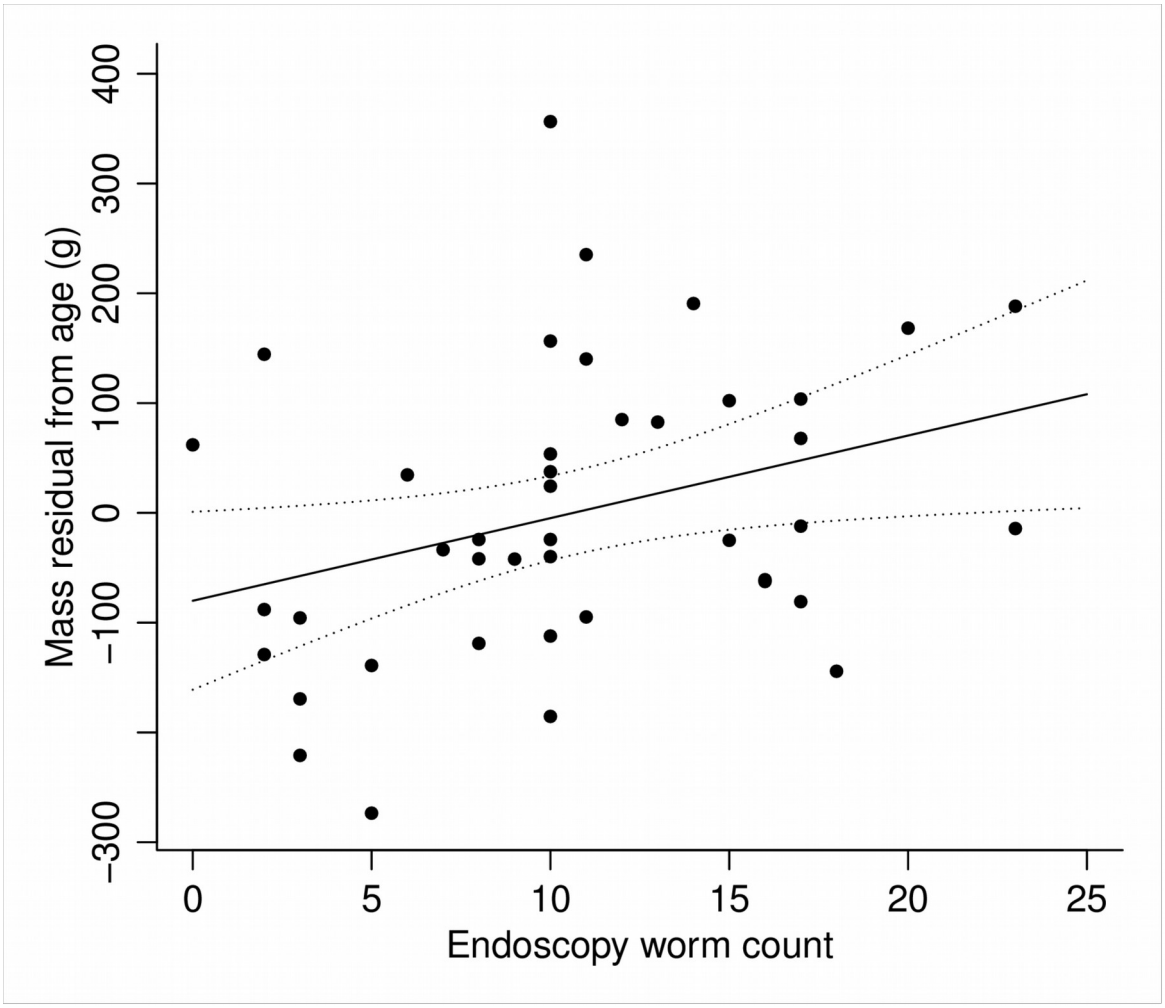


Figure 4. The relationship among endoscoped chicks between mass at endoscopy and worm count. The solid line shows the fitted relationship and the dotted line the 95% confidence intervals. To account for other factors affecting mass, mass is shown as the residual from a LMM containing age as the only predictor, following the best-fit model for chick mass.



Between-individual variation in nematode burden among juveniles in a wild host

Supplementary Information:

Using endoscopy to test the efficacy of anti-parasite treatment, observations from dissections, and patterns in faecal egg counts

Efficacy of anti-parasite treatment

Introduction

Our study system, the European shag (*Phalacrocorax aristotelis*, henceforth "shag") and its gastrointestinal nematodes, is increasingly yielding valuable insights into the effects of parasitism on individual fitness-related traits and population-level consequences in wild hosts. Although parasites are known to be important influences on host demography and evolution in wild vertebrates (Hudson *et al.* 2002; Tompkins *et al.* 2011), they are rarely considered as factors in ecological processes in seabirds, a globally threatened group whose members are often used as indicators of the state of their marine environment (Piatt, Sydeman & Wiese 2007; Croxall *et al.* 2012).

Several studies of parasitism in the shag have used anti-helminthic treatment as an experimental approach to investigate the effects of nematode infection (Reed *et al.* 2008, 2012; Burthe et al. 2013; Granroth-Wilding *et al.* 2014, 2015). The injectable, broad-spectrum antihelminthic drug, Ivermectin (Panomec©, Merial UK) has thus been shown to affect chick survival and growth, adult condition, and behaviour of both adults and chicks, strongly suggesting that treatment affects worm burden. Ivermectin also impacts on ectoparasites, yet previous evidence from this system suggests that ectoparasites contribute little to the cost of a shag's overall parasite burden (Daunt *et al.* 2001). Indeed, Burthe *et al.* (2013) used endoscopy to show that a high dose of ivermectin significantly reduced or removed worm burdens in the proventriculus of adult shags, with no evidence that infection returned for at least 20 days after treatment. In chicks, faecal egg counts (FECs) have provided an indication that treatment reduces affects worm burden, but direct evidence is lacking in chicks of how treatment at the doses used in previous studies affects worm burden. Demonstrating a real effect of treatment on *in situ* nematode burden is particularly important given that, as we show in the main manuscript, FECs in this low-shedding system may not be sensitive to small-scale variation in worm burdens.

Understanding the effect of treatment on parasite load is an important link in understanding how between-individual variation in fitness is linked to infection status in juveniles, given that anti-parasite treatment experiments have suggested that infection in chicks can affect both chick growth and parental condition, with long-lasting effects that may be important in population processes (Granroth-Wilding *et al.* 2014, 2015). Here, we use endoscopy of chicks to quantify the effect of treatment with ivermectin on worm burden in shag chicks, at the dosage used in previous work.

Methods

We combined the main endoscopy study of natural variation in parasite burden with an experiment to investigate the efficacy of anti-parasite treatment, following protocol from previous parasite removal experiments in shag chicks (full details in Granroth-Wilding *et al.* 2014). We visited nests of three eggs every two days around predicted hatching to obtain hatching dates. When the oldest chick in a brood was 10–12 days old, if all three chicks were still alive, the whole brood was injected with either 0.05ml ivermectin (Panomec© by Merial, 1% wt/vol) (drug-treated broods) or veterinary saline solution (sham-treated control broods). At treatment, we blood sampled chicks for molecular sexing (Griffiths, Daan & Dijkstra 1996) and assigned a rank in the brood hierarchy to each chick according to size, with the heaviest two assigned AB and the lightest C. We have previously shown that mass at this age correctly identifies the C chick in 90% of broods (Granroth-Wilding *et al.* 2014). Previous work has shown that responses to treatment, and therefore potentially the effect of treatment on worm burden, varied between chicks according to differences in rank, sex and hatch date (Reed *et al.* 2008, 2012; Granroth-Wilding *et al.* 2014, 2015). At or after age 25 days, we endoscoped all surviving experimental chicks (66 chicks in 29 nests; detailed endoscopy methods in the main text). We also endoscoped unmanipulated chicks from 6 nests known to have had an initial brood size of three.

We examined the efficacy of treatment on worm burden by testing whether it affected the total number of worms and the proportion of worms that were large)an indicator of the maturity of the infection). We also examined the impact of treatment on chick performance by testing whether it affected mass at endoscopy, which was positively associated with natural worm burdens in the main investigation. Unmanipulated and sham-treated chicks were pooled as the control group (see main text). All models included age as a predictor, given that older chicks host more worms and a greater proportion of large worms (see main text) and are heavier. For all three response variables (worm count, proportion large, chick mass), treatment was tested as a main effect and in interactions with

sex, rank or hatch date, factors which have previously been shown to influence the impact of treatment (Granroth-Wilding *et al*. 2014, 2015; Reed *et al*. 2008, 2012). In this directed analysis we used hypothesis-testing to assess the importance of each tested factor, in contrast to the more exploratory AIC-based model selection in the main manuscript. We were unable to robustly test the effect of ivermectin treatment on FECs as only 3 drug-treated chicks yielded faecal samples, but we provide a qualitative discussion of these data. All modelling was conducted in R 3.0.2 (R Core Team 2013) using the packages lme4 (Bates, Maechlar & Bolker 2011) and nlme (Pinheiro *et al*. 2012). Worm count was modelled with poisson errors and a log link, the proportion that were large was modelled as a binomial response (weighted by total count), and mass at endoscopy was modelled as a Gaussian response. All parameters are presented as the mean ±1 standard error.

Results & discussion

Ivermectin-treated chicks had lower worm burdens than control chicks (mean burden of ivermectin-treated chicks 8.7 ± 1.3 worms; mean burden of control chicks 11.0 ± 1.1 worms; log-transformed effect size in addition to age -0.54 ± 0.26 log(worms), $z = -2.12$, $p = 0.034$) (fig. S1). However, treatment did not affect the proportion of worms that were large (in addition to age, effect of treatment 0.34 ± 0.55, $z = 0.62$, $p = 0.537$). Sex, age and hatch date did not change the effect of treatment on either worm count or the proportion of worms that were large (all interactions $p > 0.1$). This demonstrates that ivermectin is an effective anti-helminthic in live juveniles in the wild, and indicates that it acts equally on all parts of the worm population. These results support the continued use of ivermectin in long-term experiments into the fitness impacts of parasite infection in the wild, enabling experimental work that is valuable in teasing apart correlative patterns in natural burdens and concurrent variation in host fitness.

Chick mass at endoscopy did not differ between any ivermectin-treated and control chicks (in addition to age, effect of treatment 18.3 ± 61.9, $t = 0.30$, $p = 0.771$; interactions with sex, rank and hatch date all $p > 0.3$). This is perhaps unexpected given that treatment reduced worm burden and that, among naturally infected chicks, heavier chicks had higher burdens (see main text). However, the lack of an effect of treatment on mass is consistent with between-year variation in the impacts of anti-parasite treatment on shag chicks: breeding conditions in the experimental year were such that we would expect little impact of treatment or variation between individuals (Granroth-Wilding *et al*., 2014).

Although we could not explicitly test the effect of treatment on FECs as a proxy indicator of worm burden, we noted that eggs were detected in the faeces of 16 out of 43 control or unmanipulated chicks (37% prevalence) but in none of the four drug-treated chicks for which we had faecal samples (0% prevalence). This points towards treatment reducing FECs as well as reducing worm burdens measured *in situ*. Although our main study found that egg presence in faeces does not, in this system, provide sufficient resolution to reflect natural variation in worm burdens, it is notable that previous work has shown ivermectin treatment to prevent an increase in FEC with age in shag chicks (Granroth-Wilding *et al*., 2014). Together, this suggests that FECs may be a useful indicator of artifical differences in worm burden in this system, providing an accessible though crude tool to validate the efficacy of experimental anti-parasite treatment.

Observations from dissections

As part of the main study, 33 chicks that had died naturally were dissected to obtain an alternative, direct measure of worm burden. Findings concerning between-individual variation in worm burdens are described in the main text; here, we provide a qualitative summary of observations made during dissections concerning the biology of the parasite within the host and pathology of infection.

All dissected chicks contained food, ranging from a heavily digested paste to almost-whole fish from recent feeds. Worms were found almost exclusively in the proventriculus; some worms were present in the oesophagus of two chicks, but never in the intestine. On no occasion were worms or other visible parasites observed in the body cavity outside the digestive tract. Smaller worms were found predominantly in digested food at the bottom of the stomach, whereas larger worms were found predominantly in or on recently ingested or semi-digested boluses of fish. In most dissections, worms were also found in and under the mucous lining of the stomach. Some attachment points on the stomach wall were characterised by hardened ulcerations, which were all in the upper part of the stomach, more concentrated towards the oesophagus.

Patterns in FECs

As part of the main study, we collected faecal material from 43 unmanipulated or control-treated chicks to examine how well this proxy measure reflects the more reliable indices of worm burden obtained through endoscopy and necropsy. FECs are commonly used as a non-invasive indicator of variation in worm burden, but their reliability is variable and must be verified in each new system in which they are used. In this paper, our main study revealed that eggs could only be detected at very low levels in faecal material (see main manuscript), and that FECs therefore did not capture the full extent of infection in juveniles, possibly as worms have not yet reached sexual maturity at these early stages of infection. We therefore instead investigate whether the presence/absence of eggs, indicative of an established infection,varies with *in situ* indices of worm burden and with host phenotypic traits that have previously been reported to affect how individual traits are affected by infection.

Methods

We opportunistically collected faecal samples from 19 endoscoped chicks that defecated during handling. From 24 dissected chicks, we obtained a faecal sample from the cloaca after carcasses had been frozen at -20°C for long-term storage. All faecal samples were therefore stored at -20°C after collection. Previous work in this system has given no evidence that freezing affects egg counts or prevalence (in 138 faecal samples across 3 years of chicks with natural worm burdens, stored either frozen or at room temperature in the non-distorting preservative DESS (Yoder et al., 2006), in a binomial GLMM including year as a random effect and storage method and age as fixed effects: effect of freezing compared to room-temperature DESS on egg count 0.09 ± 0.8, $z = -0.11$, $p = 0.910$; effect on egg presence -1.0 ± 0.8, $z = -1.31$, $p = 0.191$).

FECs were carried out using a flotation technique (Bowman and Georgi, 2009). The sample was fully defrosted and mixed well with 20ml saturated salt solution per 1g of faeces (sample sizes, including a variable proportion of nitrogenous waste, ranged from 0.1 to 1.2 g; mean 0.6 g). The mixture was left for c. 10 minutes to allow organic debris to settle out and the lipid-rich eggs to float up. The upper two-thirds of the water column was then mixed gently using a pipette, and an aliquot taken while raising the pipette slowly through the liquid to ensure sampling of any eggs that had not yet reached the surface. The aliquot was placed in a McMaster slide and the portion under the grid (0.15 ml) was systematically searched for nematode eggs at 40x magnification using a light

microscope. Three aliquots were examined from each bird, totalling 0.0225g of faecal material. This is sufficient to detect egg presence in adult birds in this low-shedding system (egg presence/absence in 42 adult shags with natural burdens quantified using a variable number of aliquots: using 4-10 aliquots, effect of number of aliquots on egg presence 0.02 ± 0.15, $z = 0.14$, $p = 0.882$; mean prevalence with 95% confidence intervals across 23 individuals with 10 aliquots 32 ± 20%, across 19 individuals with 4-8 aliquots 35 ± 23%; across 43 chicks with 3 aliquots in this study, 37 ± 15%).

Most of our 43 faecal samples contained no eggs and only 7 contained more than 1 egg (9 with 1 egg, 4 samples with 2 eggs, 2 with 3 eggs and one with 42). To overcome the statistical challenges presented by such a skewed distribution, FECs were analysed as a binary presence/absence response with binomial errors and a logit link. Fitting egg counts with poisson errors and an observation-level random effect to allow for this overdispersion gave qualitatively similar results. We tested whether the probability of egg presence in FECs varied with total worm burden or the number of large worms (more likely to be mature and thus producing eggs) as quantified using either endoscopy or necropsy. Model selection used AICc (details in main manuscript).

Results and discussion

Among models examining the effect of worm burden as measured *in situ* (endoscopy and necropsy combined) on FECs, nematode egg presence in faeces was best explained by a model containing only a measurement technique term (log odds of egg presence in endoscoped chicks 1.17 ± 0.70 compared to dissected chicks), although this was of an equivalent fit to an intercept-only model ($\Delta AIC = 0.3$) and a model containing containing a single large worm count term (log odds of egg presence -0.05 ± 0.06 per large worm). In relation to chick phenotypic traits, egg presence was best explained by chick age, which appeared in all three best-fit models (table S1, fig. S2). There was no strong support for any other chick traits being associated with egg presence in faeces.

Despite the lack of evidence for any relationship between the presence of nematode eggs in faeces and the more direct *in situ* indices of infection intensity, this proxy measure did reflect the increase in worm burden with chick age that we found with both necropsy and endoscopy. As worm eggs were more likely to be found in older chicks, FECs may thus have some utility for capturing natural variation (or experimental changes to natural burdens; see above) in established infections across the population. However, the variation in the data resulting from the low prevalences mean

that we cannot confidently rule out some zero counts being false negatives, and the results of the FEC analyses should therefore be interpreted with caution. Thus, endoscopy remains a more useful technique for capturing the full extent of infection for any given bird and across the population at any point in its lifetime.

738 **Bibliography**

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Table S1. The top five models of best fit explaining the presence of nematode eggs in shag chick faeces. The top set of models investigated the relationship of FECs with worm counts as measured by one of two *in situ* techniques (endoscopy or dissection) on a set of candidate models using the variables technique, worm count and proportion of large worms. The bottom set investigated variation in FECs in relation to host traits, and explanatory variables used in building the candidate model set were age, sex, rank and hatch date. Models are shown with their ΔAICc relative to the best-fit model, in order of decreasing fit. All models included a random effect of nest.

Model terms	**d.f.**	**ΔAICc**
Relationship with in situ worm measures		
Technique	3	0.0
(intercept only)	2	0.3
Large worm count	3	1.9
Large worm count + technique	4	2.3
Total worm count + technique	4	2.4
Host traits		
Age	3	0.0
Age + Hatch date	4	1.0
Age + Sex	4	1.7
(intercept only)	2	2.1
Age + Rank	4	2.1

Figure S1. Worm counts measured using endoscopy in chicks of varying ages that had been treated with ivermectin (solid symbols and line) or sham-treated not manipulated before endscopy (hollow symbols, dotted line). The line shows the fitted mixed-effects model.

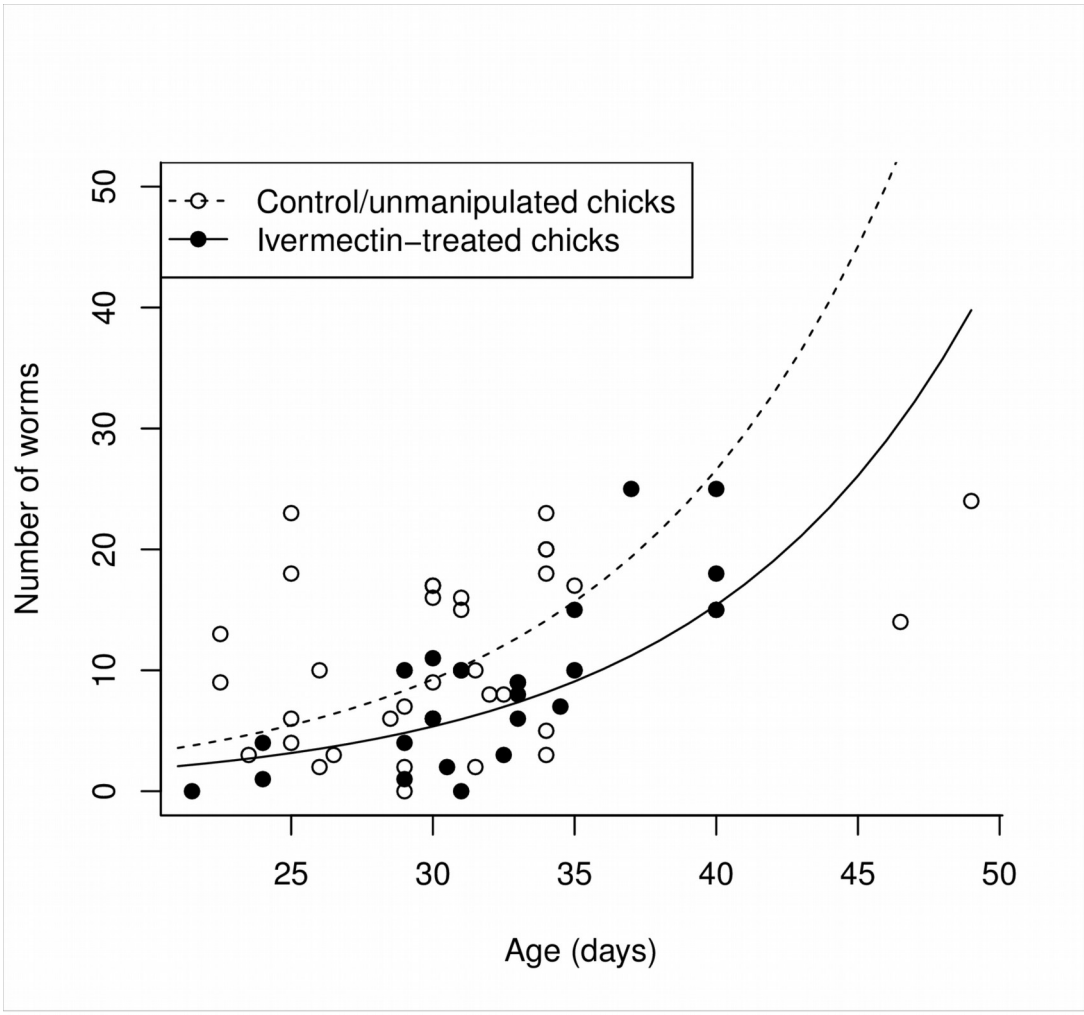

Figure S2. The relationship of egg prevalence, quantified using FECs, with chick age. The solid line shows the fitted relationship and the dotted lines its 95% confidence intervals.